Achieving High Irrigation Efficiency with Modern Surface Irrigation

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Surface irrigation has the reputation for having low irrigation efficiencies. While surface irrigation performance continues to be very low in some places, there are also many conditions for which surface irrigation efficiencies rival those of pressurized systems. There are conditions under which pressurized irrigation systems are more efficient and more economical. There are also conditions under which surface irrigation is both efficient and economical, thus resulting in higher net returns. All irrigation systems require an appropriate design to produce a high efficiency. However, surface irrigation systems are much more subject to poor operating decisions, while pressurized system demand a high level of maintenance. Good management with surface irrigation requires systems that are designed with simple operations that are less subject to the whim of the irrigator, who in many cases is not highly trained. A good example of a highly-efficient, easy-to-operate, low-capital-investment surface-irrigation system is the new drain-back level-basin system which is rapidly expanding in central Arizona.

Introduction

Surface irrigation has a reputation for poor performance. There are clearly many areas where irrigation efficiencies are low. A low irrigation efficiency by itself is not a good indicator of performance. In some hydrologic settings, the return flow from irrigation is reusable downstream and low efficiencies have little or no impact on available water supplies on a watershed basis. In other cases, irrigation return flow are not reusable – too saline or not recapturable before entering a saline sink. In such cases, improving irrigation efficiency has a very important role to play in increasing available water resources.

Many within the Irrigation Association believe that pressurized irrigation in the only way to achieve high irrigation efficiency. Critics point out the many areas where surface irrigation is practiced at low irrigation efficiency. In some cases, these low efficiencies are an economic choice – where capital investment on improved irrigation systems would not provide adequate returns. Water is used as a management tool to reduce other inputs (e.g., labor, land grading, tillage, etc.). There are also conditions under which surface irrigation is not capable of high performance – rolling topography with shallow soils, highly nonuniform soils, etc. On the other hand, there are situations where poor irrigation efficiencies cannot be justified -- including both pressurized and surface irrigation.

Water supply restrictions can limit the conversion to pressurized systems. Water supplies for much of the western United States are delivered through open channel delivery systems. There are many irrigation districts with delivery systems that would not be capable of supplying flows that are compatible with pressurized irrigation methods. In some areas, farmers have constructed reservoirs to provide a transition from these surface supplies to pressurized irrigation systems. To a lesser extent, these water delivery limitations also deter the adoption of improved surface irrigation systems.

There are conditions under which surface irrigation can achieve acceptable performance at reasonable cost. Under such conditions, conversion to pressurized irrigation may offer little advantage. In fact, it is unlikely that surface irrigation will ever be entirely replaced with pressurized irrigation, particularly when considering application worldwide. Given this view, it is still useful to develop means by which surface irrigation systems can achieve reasonable performance. In this paper, I briefly discuss surface irrigation methods that are capable of high performance and some software tools that are useful for assisting in achieving these high levels of performance.

Surface Irrigation Methods

Surface irrigation methods can be categorized according to how they function hydraulically. Key differences can be seen in the advance and recession curves, which describe the time when the advancing stream reaches a particular location and the time when standing water no longer occurs on the surface. This hydraulic comparison assumes that water enters the irrigation set along one end and flows to the other end uniformly across the set width. Categories of surface irrigation are shown in Table 1. The main differences between these categories are the magnitude of the inflow rate (and pattern) and the general shape of the recession curves and runoff hydrographs. These systems are hydraulically different, have different operating conditions, and thus different limits on their potential.

Table 1. Categories of Surface Irrigation

Method	Control of lateral flow	Slope	Inflow control	End conditions
Sloping Furrow	Furrows	· Steep or · Low-gradient Either can have cross slope	To individual furrows	· Open, · Partially blocked · Blocked, or · Group of furrows blocked
Border strip	· Flat planted · Corrugations	· Steep or · Low-gradient Can have cross slope	Distributed across upper end	· Open, · Blocked, or · Partially blocked
Level Basin	· Flat planted · Furrowed or bedded	Zero in all directions	Can be point inflow	Blocked If furrowed, all interconnected
Level Furrows	Furrows	Zero in direction of run, can have cross slope	To individual furrows	· Blocked, or · Group of furrows blocked

Achievable Irrigation Efficiencies

Irrigation efficiency is often confused with application efficiency or with the fraction of irrigation water consumed. These are all actually very difference concepts. Burt et al 1997 define *Irrigation Efficiency, IE,* as *the volume of irrigation water beneficially used divided by the difference between the irrigation water applied and the change in storage*. It is really an after-the-fact determination of what happened to the applied irrigation water. Water is storage has not yet been used and so does not count toward irrigation efficiency. It is often mistakenly assumed that water that is not beneficially used is somehow lost and not available for reuse elsewhere. This is often not the case, since tailwater runoff and deep percolation in many irrigated settings returns to the hydrologic system and is used downstream. From a water supply standpoint, only water that is consumed or severely degraded in quality is not available for reuse. Because crop evapotranspiration is the largest beneficial use, IE is often mistakenly assumed to be related to the fraction of irrigation water consumed.

Very few assessments of irrigation systems actually determine irrigation efficiency, since the real data needed for such an evaluation is extremely difficult to obtain. For example, to determine irrigation efficiency for a field, one would have to know how much water was actually used by the crop, not just an estimate based on uniform conditions. Separating irrigation water use from rainfall use can also be a real challenge. As a result, an evaluation of irrigation system performance usually determines the performance of a particular irrigation event. *Application Efficiency, AE,* measures the performance of an irrigation event, and reflects how well that irrigation satisfied the objective of irrigating. It is defined as the *average depth of irrigation water contributing to the target divided by the average depth of irrigation water applied*, where *target* means target depth of application (e.g., soil moisture deficit).

The uniformity of irrigation can severely limit the performance of an irrigation event. Under irrigation of parts of a field limits the effectiveness of the irrigation. To judge this effect, Burt et al (1997) define the low-quarter adequacy as the average low-quarter depth divided by the target or required depth. If the low quarter depth is less than the target depth, then the target depth is reduced to the low quarter depth for calculating application efficiency.

Reported values of irrigation efficiency are often very misleading. They often reflect the application efficiency of a particular event, but based on an estimated soil moisture deficit and not on the intent of irrigation. Also, such efficiencies are often inflated if they do not consider the distribution uniformity and low-quarter adequacy. The later often results in reports of efficiency greater than 100%! While surface irrigation systems often have the reputation as being inefficient, data from mobile irrigation laboratories in California (Kennedy 1994) suggest that for well designed and managed systems, differences in efficiencies between surface and pressurized systems are small. (These are application efficiencies reported as irrigation efficiencies). Thus under ideal conditions, surface system efficiencies may approach those of efficient pressurized systems. There are many situations under which these high efficiencies cannot be attained with surface irrigation. Thus surface methods tend to have a wider range of attainable efficiencies. Figure 1 provides a rough estimate of attainable application efficiencies for the various methods. More details can be found in Bliesner et al (1998).

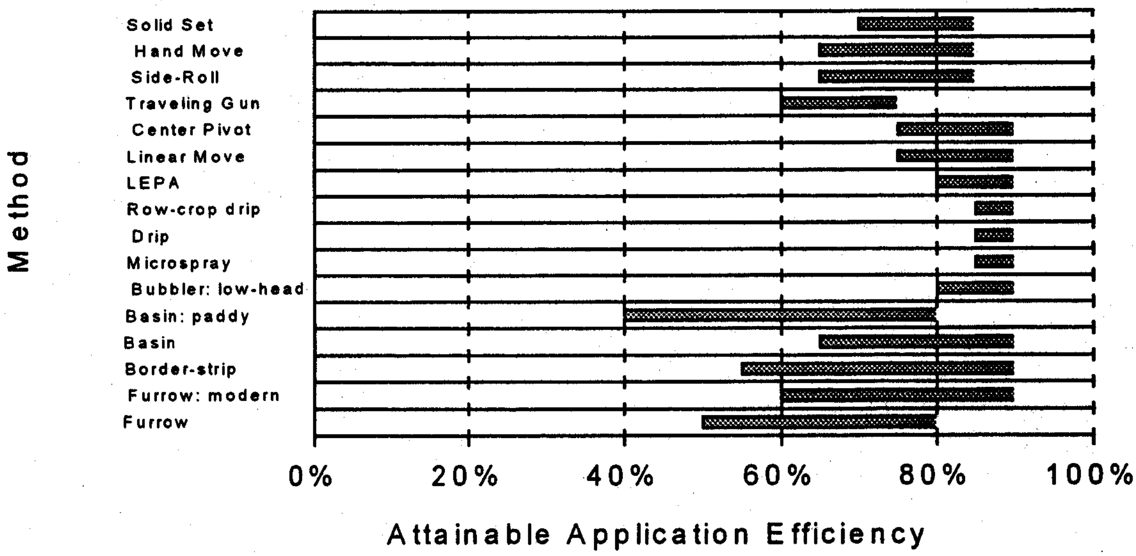

Figure 1. Attainable application efficiencies (adapted from Clemmens and Dedrick, 1994).

Modern Surface Irrigation Methods

Even under conditions where surface irrigation has the potential for high performance, high performance is often not achieved, typically resulting from poor design and/or poor management. Modern surface irrigation implies systems that are designed and managed to achieve high efficiency through improved water measurement and control.

Sloping Furrow Irrigation: The ability to control and adjust inflow to individual furrows has a major impact on the performance of sloping furrow irrigation systems. Because recession occurs relatively quickly in sloping furrows, advance must also be relatively fast in order to provide uniform infiltration opportunity time from one end of the field to the other. Fast advance is achieved with a high flow rate, which often results in large runoff rates and volumes. Without adjustment of inflow rate (e.g., after advance), application efficiency will be low. Likewise, advance must be even across the set width. If advance is highly nonuniform from furrow to furrow, excess runoff may occur in the faster furrows in order to adequately irrigate furrows with slow advance. Thus improved control includes both control of flow from furrow to furrow, and control of flow over time. Without this control, advance will be highly nonuniform and runoff rates will be high, both of which generally lead to poor efficiency.

Several methods have been developed to control individual furrow inflow over time, including cutback, surge, and cablegation. With cutback, the inflow is reduced after advance is complete, typically to half the original inflow. This is usually accomplished for an entire set by controlling the water level in the supply channel, where individual spiles or weirs supply water to individual furrows (Eftekharzadeh, et al 1987). With gated pipe, it is difficult to accurately control individual furrow flows for an entire set. Surge irrigation resulted from attempts to achieve cutback flows with gated pipe. However, it was found that when the soil was wetted intermittently the infiltration rate tended to decrease between wettings. The net result is reduced water infiltrated during advance. After advance is complete, the flow is split between two sets to achieve cutback. Several companies manufacture and sell surge valves. These have been highly successful at improving application efficiency (Yonts, et al 1996). Cablegation also provides a way of reducing the inflow from gated pipe over time and thus reducing runoff (Kemper et al 1981). An alternative to controlling inflow is to capture and reuse runoff. Tailwater reuse systems are used to capture water that runs off during furrow irrigation. Adjusting irrigation flows, set widths, and application times to balance inflow, outflow and storage capacity can be challenging. Often a tailwater return system services an entire farm rather than a single field.

Sloping Border Strips: The efficiency under sloping border-strip irrigation is limited by the choice of flow rate and application time (or advance distance at cutoff criteria). The decision on flow rate and cutoff criteria is made prior to the irrigation, and frequently when setting up the strips (i.e., deciding on border spacing). As conditions change during the irrigation, the best choices for flow rate and cutoff may change. It is a challenge for the irrigator to adjust rate and time to maintain high performance for each irrigation. A good deal of research effort has gone into methods for estimating infiltration and roughness conditions and optimizing flow rate and application time, however, these are not yet usable at the field level. Proper selection of flow rate and cutoff criteria over the season can lead to reasonable performance. Other methods for improving performance include; reducing the slope, reducing the slope at the lower end, and blocking the end. Surge, cutback, and tailwater return systems offer less advantages, since water is usually cut off prior to completion of advance.

Level Basins and Level Furrows: Proper design is the key to high level basin and level furrow performance. In contrast to sloping irrigation where the water surface gradient is provided by the field slope, with level basin and furrow irrigation the water must build up on the field surface to provide the water surface gradient that drives the advance. If the basin is very long, the water depth at the head of the basin becomes large, resulting in a large depth of application. The challenge is to make the basins sufficiently small such that reasonable application depths can be efficiently applied. If the basins are small enough and soils are uniform enough, very high efficiencies can be attained. For many soils, the basin lengths are shorter than desired for machinery operation, or result in water application depths that are too large. Larger flow rate provide faster advance and thus greater distribution uniformity. However, there is a point where a higher flow rate no longer helps and actually results in too great a volume applied. Soil infiltration variability and undulations in the soil surface also have more impact on uniformity where water is ponded (e.g., blocked from running off).

Level-basin irrigation has been practiced for centuries, but it was the development of laser-controlled land grading in the 1970s that made level basins a practical alternative for achieving high application efficiencies with surface irrigation (Dedrick 1984). The Arizona Department of Water Resources uses level basins as the standard for achieving their target irrigation efficiency of 85%, which is used to determine water duties. Many farmers have complained that the expense of conversion to level basins is too high since it often requires them to break up their fields into smaller blocks. However, the recent innovation in level basins – drain-back level basins – has greatly reduced the development cost of level basins, allows much smaller irrigation depths to be applied, and provides surface drainage, a necessity under some conditions (Rayner 1998, Dedrick 1997).

A drain-back level-basin system is a series of level basins that are benched. The irrigation canal is constructed below grade so that it can provide both irrigation and surface drainage. At each bench, the canal has a check. When a check is closed, the irrigation canal fills with water and irrigates the field. When the advancing water reaches the end of the basin, or sometime soon thereafter, the check is opened. The water in the canal flows down to the next lower-lying basin. The water also flows off the already-irrigated basin back into the canal and provides a larger flow rate to the next basin. Thus the water used to provide the gradient to drive the water advance is drained off. Thus one can use a higher flow rate to speed advance and improve uniformity with less fear of over irrigation. Research has shown that 50% of the water on the surface can be drained off.

The drain-back irrigation canal is a very wide shallow earth channel with a gradual transition up to the field surface. When properly constructed, it can serve as the turn row for equipment. Water flow onto the field is very gradual and non-erosive. The water draining back off the field can be slightly erosive at first, but stabilizes quickly. A cross section of the irrigation/surface-drainage canal is shown in Figure 2. To properly drain on basin into the next lower-lying one requires about 30 cm (1 ft) elevation change between basins. The bottom of the irrigation canal is typically 30 to 40 cm (12 to 15 in) below the field grade. Flow rates of 350 to 500 l/s (12 to 18 cfs) for a 4 ha (10 ac) basin are common. For furrows, application depths of 4 cm (1.6 in) with reasonable uniformity can be accomplished.

The drain-back level-basin system also offers significant reductions in development cost over more conventional basins. Development cost for drain-back systems are less than half that of conventional systems -- on the order of $650/ha ($260/ac) for drain-back compared to $1500/ha ($600/ac) for conventional basins. Much of this savings results from not having to install concrete lined ditches or turnout structures. Labor savings with either basin method over sloping irrigation are similar. One farm went from 6 to 1 irrigator for 1000 ha (2500 ac) when converted from sloping furrows to drain-back level basins.

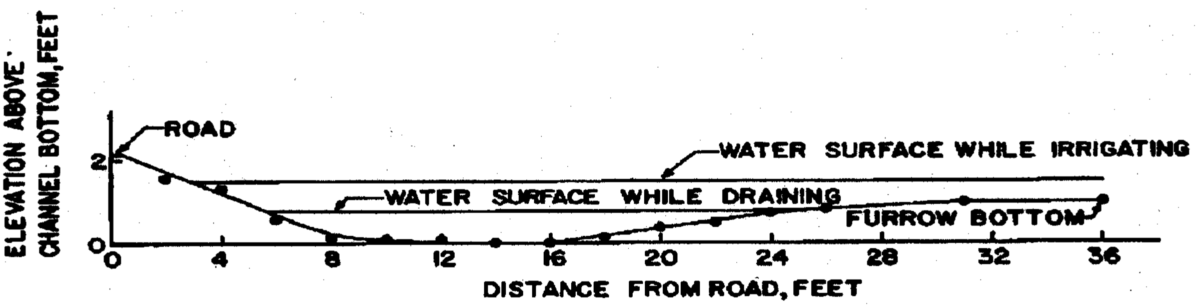

Figure 2. Cross sectional view of irrigation canal for drain-back level basin.

Software for Simulation, Design and Management

Calculation of water flow through pipes, nozzles and emitters is relatively straightforward. Reasonable calculation methods have been available for more than a century. In contrast, calculation of water flow in surface irrigation is extremely complicated – the equations are complex and numerical solution procedures are required. The first practical model for calculation of surface irrigation flow was developed in the mid 1970's. That model has evolved into the current surface irrigation simulation model, SRFR (Strelkoff et al 1998). The SRFR model is capable of modeling water flow down a single furrow or down a unit width (i.e., 1 m or 1 ft wide) strip of a border strip or basin. It is essentially one-dimensional – down the length of run. To operate this model, you have to provide all the details of the irrigation, including

design information – length, slope, furrow cross section and spacing, end conditions, etc.
soil and crop properties – infiltration, flow resistance
management – inflow hydrograph (e.g., flow rate and application time)

The output from this simulation is a distribution of infiltrated water down the length of run and a runoff hydrograph. The program allows a wide variety of inputs, including surge flow. Three commercially available surge valves have been programmed into SRFR so that inflow is generated the same as if they were being programmed in the field.

The simulation program is very useful for determining the results for a particular set of conditions, but it cannot directly give advice on the best design or the best operations. To develop these recommendations would require repeated simulation with different conditions to arrive at some optimum choice. Most existing surface irrigation design methods do not utilize these simulation models, but instead rely on conservation of mass and empirical relationships that "approximate" typical conditions. In some cases, these empirical design guidelines have resulted in very poor designs.

For two situations of interest, repeated simulations with a surface irrigation model have been performed to provide design guidance. The first was done for level basin irrigation systems (Clemmens et al 1995), the second for sloping border irrigation systems (Strelkoff et al 1996). With the BASIN program, the user enters a specific set of infiltration and roughness conditions and a target infiltration depth. The program provides the user with the choice of which design parameters to set and which to compute, between inflow rate, length, width, potential AE (called DU in the program), and cutoff criteria. For each choice of inputs, the user is provided with one set of design output. For example, if you give the program the inflow rate and the desired potential AE, the program will provide the length and width required to give that AE value, along with the application time, advance distance at cutoff, and other information. The BASIN program adequately covers the full range of level basin conditions of interest, but is limited in its choice of infiltration equations.

The BORDER program is much more flexible. Rather than providing a single output, it provide a two-dimensional map of performance over a range of two input variables. For example, if you provide the program with infiltration and roughness conditions, a target depth, and border width, the program will plot a contour map of potential AE (and other performance parameters) as a function of both border length and inflow rate (Figure 3). This graph allows one to determine the range of lengths and widths that will provide the best performance. BORDER currently has a fairly narrow range of conditions over which design solutions are available, which limits its applicability.

A new design program is being developed for design of sloping furrows (Clemmens et al 1998). For this program, the simulation program SRFR is run for one set of conditions so that simplified design solutions can be "*tuned.*" This allows designs to be performed for a wide range of conditions without the need to precompute solutions as was done for BASIN and BORDER. This tuning essentially overcomes the limitation of the simplified design approaches. Hopefully this will provide the best of both worlds. Unfortunately, the biggest limitations with the use of both the design and simulation programs is obtaining good estimates for infiltration and roughness. Roughness can usually be estimated reasonably well from standard tables. Infiltration usually requires field evaluation. Standard handbook values or families have not proven to be adequate. While many methods are available for estimating infiltration from field measurements, no convenient software exists.

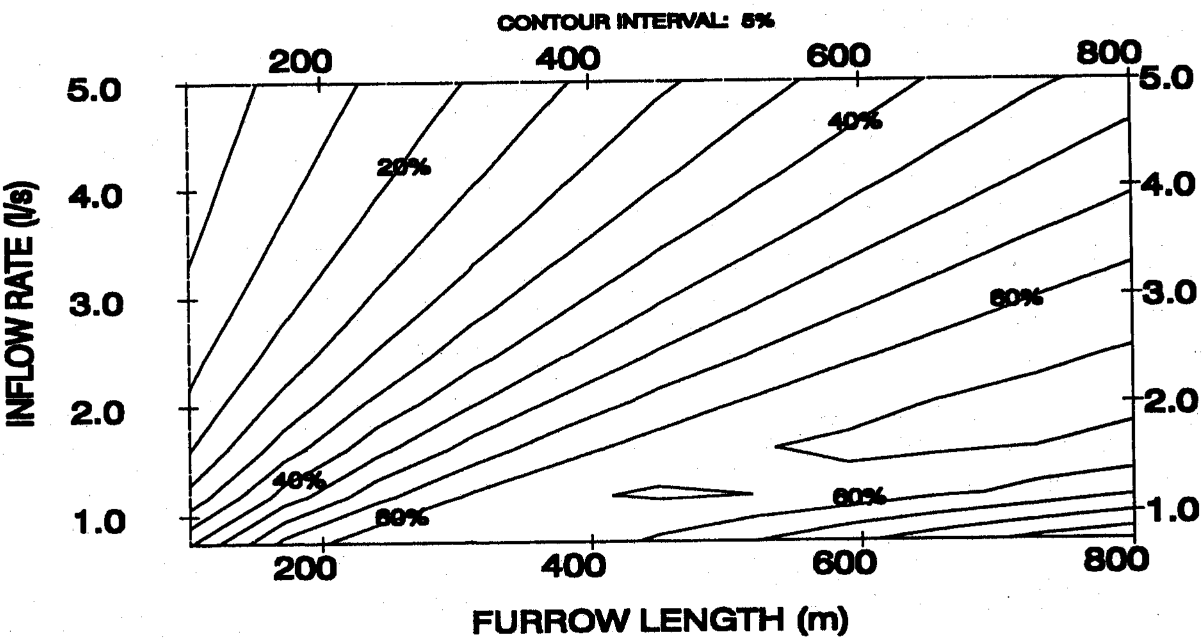

Figure 3. Potential AE for border strip for one specific set of conditions.

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